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# RF MODAL QUANTITY GAGING

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## ABSTRACT

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The primary objective of this paper is to provide a concept exposition of a radio frequency (RF) modal resonance technique which is being investigated as a method for gaging the quantities of subcritical cryogenic propellants in metallic tanks. Of special interest are the potential applications of the technique to microgravity propellant gaging situations. The results of concept testing using cryogenic oxygen, hydrogen, and nitrogen, as well as paraffin simulations of microgravity fluid orientations, are reported. These test results were positive and showed that the gaging concept was viable.

## INTRODUCTION

Techniques for the routine, reliable, and safe handling of subcritical cryogenic propellants under conditions of low to zero gravity are essential to resupply operations of future space-based systems such as an orbital vehicle (OTV). One of several technology areas critical to on-orbit management of such propellants is quantity gaging.

A major objective of the work reported in this paper is the development of a high selection merit (i.e., safe, reliable, low weight, etc.) technique for the quantity gaging of subcritical cryogenic propellant oxygen and hydrogen. The ultimate accuracy goal is  $\pm 1$  percent of full loaded mass. The current development activities have a feasibility cut-off limit of  $\pm 5$  percent. The gaging technique will be appropriate to a wide range of tank sizes and shapes with minimal gaging system weight or power requirements.

## RF GAGING CONCEPT

Using electromagnetic waves to assess the density of a dielectric medium is not a new idea; it has been investigated and implemented in many forms. Attempts to apply the technique to cryogenic propellants were especially intense during the late 1960's and early 1970's. These efforts resulted in the development of approaches that were straightforward and accurate for normal gravity situations, but were potentially much less accurate in microgravity applications. The uncertainty about microgravity accuracy, and the fact that less complex and inexpensive alternatives were usually available for normal gravity gaging assignments, discouraged further development of the approach for a 10-year period.

Strong advantages of the approach involving spaceborne, two-phase cryogenic propellant tankage applications, plus the impressive technological advancements in the relevant fields of instrumentation and electronics, led to selecting the approach for microgravity applications. Key advantages and disadvantages of the RF modal quantity gaging technique are listed in Table I.

## OPERATING PRINCIPLE

The operating principle of the basic RF quantity gaging technique is based on the following three ideas:

1. Electromagnetic energy introduced into a closed metallic cavity forms repeatable stationary field patterns at certain frequencies known as resonant modes.
2. Frequencies of these resonant modes are dependent upon the physical attributes (size and geometry) of the cavity boundaries, and on the electrical attributes (conductivity, permeability, and dielectric constant) of any medium that might be uniformly dispersed throughout the cavity volume.

1 Another JANNAP 1989 paper entitled "On-orbit Fluid Quantity Gaging by Adiabatic Compression" by A.J. Word et al of BASG also addresses this technology.

2 This introductory exposition of operating principle assumes uniform dispersion of dielectric media in the gaged cavity. What occurs when this assumption is not true is developed later in the discussion.

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Table I. Advantages and Disadvantages of RF Modal Approach.

Advantages:

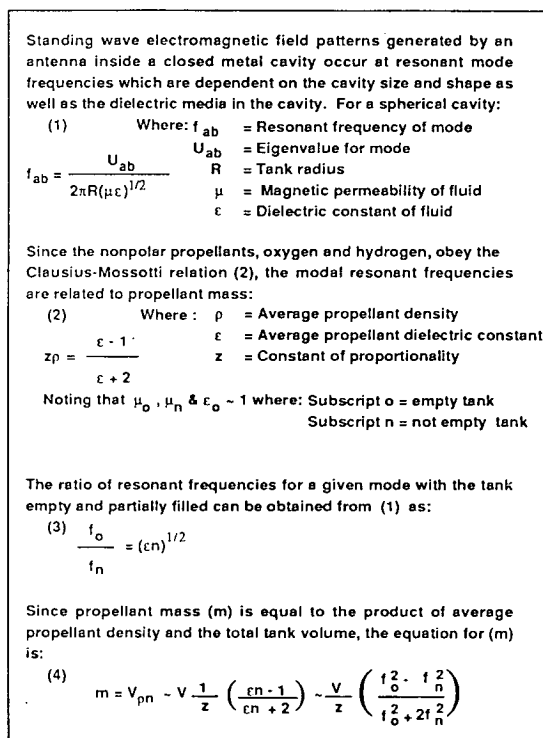
- Low-weight system, and weight does not significantly vary with tank size.
- Minimal intrusion into tank.
- Small impact on PV structure and MLI of cryogenic tanks.
- No moving parts.
- No special materials, components, or processes are required.
- Electronics located remotely from tank.
- Operating power is low and power input to fluid is negligible.
- Concept particularly applicable to propulsion cryogenics.
- Not sensitive to thermodynamic properties of gaseous fluids.
- Not affected by species of pressurant gas.

Disadvantages:

- Mass conversion algorithm development is required for each different tank configuration.
  - Requires calibration to develop correction algorithm for fluid location effects.
  - Is not easily adapted to widespread metallic constructs inside gaged tank.
  - Not applicable for use with nondielectric fluids or dielectric fluids with significant loss tangents.
- \* All except the last can be overcome.

3. If the medium in the cavity volume is a nonpolar dielectric fluid that is low loss and obeys the Clausius-Mossotti equation relating density and dielectric constant, the resonant mode frequencies are also dependent on the medium density.

Because the cavity volume is known, a determination of medium density leads immediately to mass or quantity of medium in the cavity. The equations illustrating these ideas as applied to a spherical cavity are shown in Fig. 1.



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Figure 1. Spherical Cavity Relations.

This basic form of the RF quantity gaging technique is entirely usable for situations where the medium is uniformly dispersed throughout the cavity (i.e., full and empty are special cases of this). Also, with calibration, this basic technique would likely be adequate for fixed fill and deplete orientations in a gravity field sufficient to form repeatable fluid/vapor interfaces. Zero or microgravity applications with indeterminate fluid orientation require augmenting the technique because the modal frequencies are also dependent on the spatial orientation of dielectric fluid in the cavity. This follows from the fact that the stationary field patterns at the resonant modes do not sample the cavity volume uniformly.

The ability to deal with microgravity conditions and indeterminate fluid orientations is a very desirable attribute of a subcritical cryogenic propellant quantity gaging system. For the RF gaging concept to have this capability, the basic gaging approach requires modification or augmentation. The better known approaches to this are discussed in the next subsection.

#### VARIOUS APPROACHES

Techniques for adapting the RF gaging concept to microgravity random fluid orientation situations have been based on the following two approaches.

Mode Counting. The Instruments and Life Support Division of the Bendix Corporation developed this technique in the late 1960's. It is based on the theoretically derivable fact that the number of modes that can be established within a cavity over a specified frequency band is linearly dependent upon the amount of dielectric medium in the cavity. If the frequency band limits were chosen to give a full cavity total mode count of one to two thousand, the resulting large number of stationary field patterns would sample the cavity contents so thoroughly as to become independent of dielectric medium orientation.

Normal gravity tests of the approach met the goal of 2 percent accuracy. Near zero-gravity tests in a KC-135 aircraft induced a significant number of hybrid modes and degeneracies, which resulted in readings differing from the normal gravity calibrations by as much as 18 percent of full load.

Modal Analysis. This technique, pioneered by the Cryogenics Division of the National Bureau of Standards in the early 1970's, was based on exciting the cavity over a relatively narrow frequency band and determining the resonant frequencies of only a few modes. The resonant frequencies of these modes were used in a weighted average relation to determine the mass of dielectric in the cavity.

Normal gravity testing results indicated that the technique was capable of accuracies of  $\pm 1.2$  percent of full load. Subsequent near zero-gravity tests in a KC-135 aircraft also encountered hybrid modes (i.e., those responses not predicted by classical theory) and showed that modal frequencies could vary as much as 15 percent by changes in the geometry of a constant mass of dielectric medium. Enhanced data reduction methods were required to bring the accuracy of the KC-135 test data within  $\pm 3$  to  $\pm 5$  percent of full load. These methods involved removing hybrid mode responses and time averaging the working mode responses over a 30-second interval prior to using the weighted average relation to determine the dielectric medium mass.

#### SELECTED APPROACH

A modal analysis approach was selected to minimize the effects of hybrid modes expected in microgravity applications. The resulting narrow frequency band would limit the number of hybrid modes that could be encountered. Taking this idea even further led to a decision to use the lowest four non-hybrid modal frequencies that could be excited in the cavity. It was believed that only two or three modal responses would be required to uniquely determine the dielectric medium mass, but this was yet to be verified.

Advances in frequency counter and sweep oscillator technology made it reasonable to use an approach that would directly measure and store the frequencies of up to 70 responses that could be obtained covering a four-mode frequency band in a small fraction of a second. The precision of these frequency measurements could be expected to have errors so low ( $\pm 0.005$  percent) as to be negligible in their contribution to the approach accuracy.

The modal analysis that would operate on the measured frequencies would have the following basic structure:

1. Sort the response population into groups of frequencies associated with each mode.
2. Analyze each frequency group to determine the mode frequency.
3. Use the mode frequencies (2 to 4) to classify the response and compute a mass estimate.
4. Compute any required corrections and add to the mass estimate to obtain the measured mass.

This makes up the selected approach in which the modal analysis was to be based on frequency data only. Use of other ancillary response information, which could be obtained with increased system complexity, such as relative response strength and sharpness ( $Q$ ), would be avoided if at all possible.

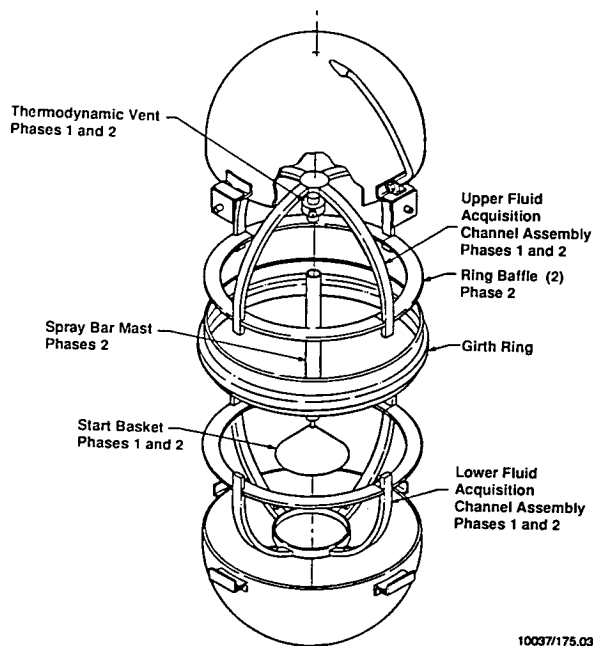
### CRYOGENIC TESTS

Feasibility testing of the selected RF gaging approach was accomplished using a laboratory equipment implementation of the RF modal gaging system to excite and detect the modal responses of a specially designed test tank. The objectives were to provide experimental assessments of:

1. The probable accuracy, repeatability, and hysteresis of a gaging system for liquid oxygen and hydrogen propellants.
2. The sensitivity of the gaging approach to variations in fluid/vapor interface location and tank internal components.
3. The suitability of tank/fluid  $Q$  to the gaging approach.

### METHOD

Test objectives were addressed using the following four test sequences: (1) characterization tests using liquid nitrogen as the test fluid to debug the test setup and perfect details of the operating procedures; (2) baseline tests using liquid nitrogen, oxygen, and hydrogen to obtain bare tank modal responses at all test attitudes; (3) Phase 1 tests using liquid nitrogen to obtain modal responses of the tank in various attitudes containing dummy fluid acquisition channels, a start basket, and a thermodynamic vent; and (4) Phase 2 tests using liquid nitrogen to obtain modal responses of a tank containing all Phase 1 components as well as a dummy spray bar mast and two ring slosh baffles. An exploded view of the internal componentry is shown in Fig. 2.



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Figure 2. Tank Internal Components.

The tank used for all cryogenic tests was designed for suspension in a vacuum chamber with shrouds operating at liquid nitrogen temperature. More detailed descriptions of the test hardware are provided below.

**Modal Gaging System.** Laboratory implementation of the RF modal gaging system used in all test sequences is shown in the block diagram of Fig. 3. In this setup, the spectrum analyzer/ tracking generator supply a constant power level signal whose frequency is periodically swept from a low to high frequency limit linearly with time. This signal is applied to any of the three tank antennas through a directional coupler. The tank antennas are deliberately mismatched over the test frequency range so that a significant portion of the incident signal is reflected. A connection to the directional coupler reflected power port allows monitoring and display of the reflected power level on the spectrum analyzer scope screen as a function of the instantaneous frequency. As the RF signal is swept over the test frequency range, the various tank resonances (modes) that can be excited by the tank antennas permit the antennas to supply more of the incident power to the tank RF fields. This results in a reduction of the reflected power level being monitored on the spectrum analyzer display. The width and depth of the resonant dips occurring in the analyzer display as the test signal is swept through the tank resonances are directly related to the  $Q$  and strength of the modal responses.

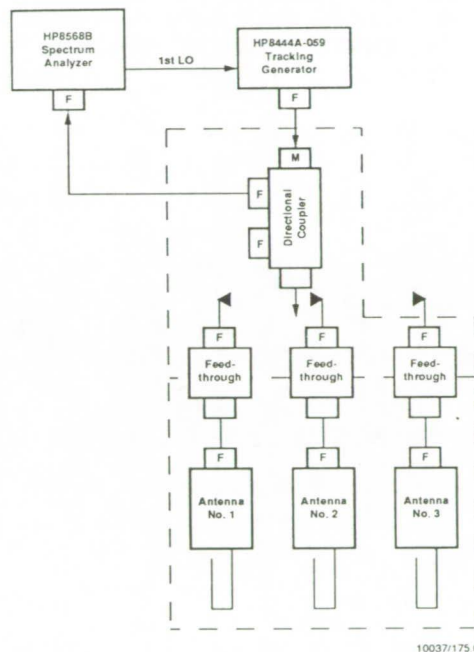


Figure 3. Modal Gaging System Block Diagram.

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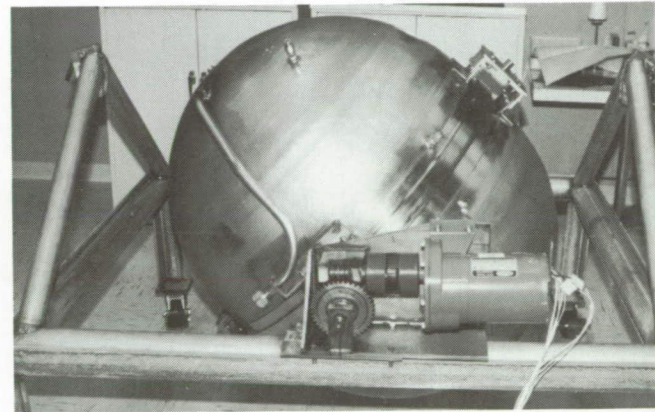


Figure 4. Cryogenic Test Tank Before Insulation.

**Test Tank.** The tank shell consisted of two 91-cm (36-in.) diameter hemispherical heads with 10-cm (4-inch) straight sections which terminated in reweldable closures. This provided an empty tank volume of  $0.536\text{m}^3$  ( $18.94\text{ft}^3$ ) and the closures permitted the test tank to be separated at the girth to accommodate changes in the internal components. Because the tank was to contain cryogenics, a removable system of multilayer radiation blankets, consisting of two offset blankets of 15 layers of double aluminized mylar with nylon net spacers, was used. The tank was mounted in a rigid tubular framework which provided two crossed-link load cell suspension points and a tank rotation system. The rotation system consisted of a worm drive to a pinion gear on the tank axle. A photograph of the tank in the test fixture prior to insulation is shown in Fig. 4.

#### CRYOGENIC TEST RESULTS

Results of the cryogenic testing effort were positive and indicated that the RF modal gaging approach was viable. The assessment objectives and corresponding test results are provided below. Definitions of parameters used in the results tables are as follows:

Probable accuracy - Most probable percentage difference between actual loaded mass and a mass computed using an algorithm employing modal frequency data. The algorithm incorporates fluid location correction capability only. Values are expressed as percent of full load.

Repeatability - Comparison of two readings of same fill level, attitude, and configuration with data taken in independent measurement cycles. Table value is highest deviation value found expressed as percent.

Hysteresis - Comparison of two readings of same fill level, attitude, and configuration with the data taken in a continuous cycle.

Fluid location sensitivity - Worst-case deviations from reference attitude value regardless of the attitude of occurrence. Expressed as percent of full load.

Sensitivity to internal components - Probable accuracy values for Phase 1 and Phase 2 configurations minus the LN<sub>2</sub> Bare Tank probable accuracy. Expressed as percent of full load.

First Objective. Evaluation of probable accuracy and repeatability gave the results summarized in Table II. No measurable hysteresis effects were found.

Table II. Cryogenic Test Results - Accuracy.

TEST FLUID	TANK CONFIGURATION	PROBABLE ACCURACY*	REPEATABILITY
LN <sub>2</sub>	Bare Tank	±1.05%	0.024%
LO <sub>2</sub>	Bare Tank	±1.61%	0.059%
LH <sub>2</sub>	Bare Tank	±0.92%	0.036%
LN <sub>2</sub>	Phase 1 Config.	±2.61%	0.078%
LN <sub>2</sub>	Phase 2 Config.	±3.65%	0.131%

\* Corrected for fluid location

Second Objective. Assessment of the gaging approach sensitivity to fluid location and tank internal components is summarized in Table III.

Table III. Cryogenic Test Results - Sensitivity.

TEST FLUID	TANK CONFIGURATION	FLUID LOCATION SENSITIVITY*	SENSITIVITY TO INTERNAL COMPONENTS
LN <sub>2</sub>	Bare Tank	±6.78%	(Not Applicable)
LO <sub>2</sub>	Bare Tank	±8.32%	(Not Applicable)
LH <sub>2</sub>	Bare Tank	±10.31%	(Not Applicable)
LN <sub>2</sub>	Phase 1 Config.	±6.21%	±1.56%
LN <sub>2</sub>	Phase 2 Config.	±7.69%	±2.60%

\*Moment analysis methods suggest the upper bound on this sensitivity should be ±15% of full load.

Third Objective. Direct measurements were made of tank/fluid Q to determine if a computed minimum value of 5,400 (the value required to obtain 0.1 percent resolution of modal frequency changes) could be realized. The lowest Q value measured was 7,800 which more than met the resolution criteria.



## BENCH-TOP TESTS

Cryogenic feasibility testing provided performance data for a wide variety of liquid attitudes in the test dewar, but did not provide any data for single bubble, wetted wall, or floating globule liquid interface configurations which could be encountered in near zero-gravity space flight. It was considered vital to challenge the RF modal gaging approach with these types of fluid distributions as early in the feasibility evaluation as possible. The primary objective of this testing effort was to assess the performance of the RF modal gaging approach when challenged with liquid configurations representative of near zero-gravity conditions.

To accomplish this, an algorithm for converting RF modal responses into loaded fluid quantity was to be developed using the zero-gravity simulation data. This algorithm was then to be used to determine the mass of five random fluid configurations. A resulting accuracy of  $\pm 5$  percent of full load was required for the concept to be considered feasible. The test method used to implement these activities is described below.

### METHOD

Certain refined grades of paraffin are good simulants for cryogenic fluids in tests investigating fluid response to electromagnetic fields. These paraffins are solid at room temperature and can be easily formed -- all characteristics that permit the simulation of zero-gravity fluid orientations in a normal gravity environment. Once the method for simulating the zero-gravity fluid orientations was found, it became desirable to work with a tank physically smaller than the cryogenic test tank, because this would reduce the scope of the paraffin forming tasks to more manageable sizes. This objective was bounded by the upper frequency limit of the laboratory equipment which would implement the RF gaging concept (smaller tank size meant higher frequencies). Also, a change in tank size would permit verification of the cavity size scaling relations, just as the use of paraffin would test the scaling of dielectric constant. This was called the bench-top test series.

Modal Measurement System. The RF modal frequency measurements system used in the bench-top test series was the same as that used in the cryogenic tests, except that the test tank had eight antenna positions instead of three. The additional antenna positions were incorporated for further investigating the effects of antenna placement.

Test Tank. The test tank was scaled as close to a half-size version of the cryogenic test tank as the use of standard stainless steel heads would permit. This resulted in using 48-cm (19-in.) diameter hemispherical heads with 5-cm (2-in.) straight sections. The upper and lower sections of the tank were held in place and made electrically continuous with a simple band around their junction. The tank shell was 4.85-mm (0.191-in.) thick to provide a substantial degree of rigidity, but was not pressure tight. Figure 5 shows the bench-top test tank.

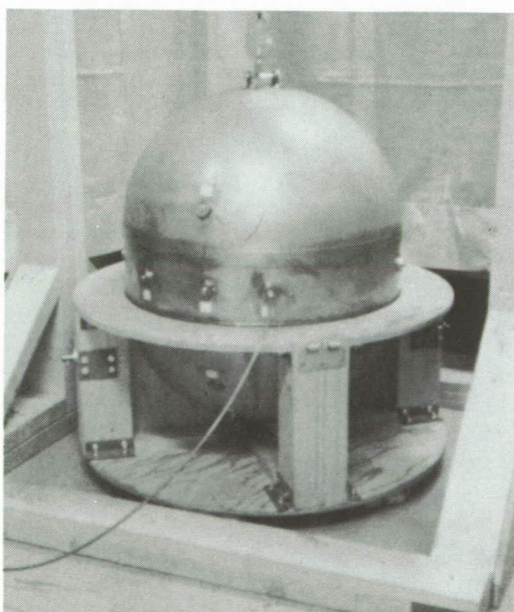


Figure 5. Bench-Top Test Tank.

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## BENCH-TOP TEST RESULTS

The RF modal gaging approach was able to successfully meet the challenge of the paraffin simulations of zero-gravity fluid orientations. Results are provided for an algorithm which computes tank loaded mass given a required set of three modal frequencies, and for an integrated algorithm which computes tank-loaded mass given all modal responses in the sweep range. The latter algorithm incorporates the ability to select the required set of three modal frequencies from the raw response data. In both instances, the algorithms were developed using 31 different fluid orientations and then tested using 5 random fluid orientations. Table IV shows accuracy performance for both the 31 algorithm development orientations and the 5 random orientations.

Table IV. Bench-Top Test Accuracy Performance.

ALGORITHM TYPE	FLUID ORIENTATIONS	ACCURACY PERFORMANCE (AVG)
Mass Only	31 Development	$\pm 0.28\%$
Mass Only	5 Random	$\pm 0.90\%$
Integrated	31 Development	$\pm 1.42\%$
Integrated	5 Random	$\pm 1.52\%$

## ALGORITHMS

From the beginning of the RF modal feasibility assessment, a method for transforming modal frequencies into a measure of dielectric media mass was necessary. Such a transformation requires 2 basic constituents, an algorithm for extracting the 3 wanted modal frequencies from a group of 21 responses (on average), and an algorithm to compute the mass of dielectric medium using the 3 modal frequencies. Initially, extraction was accomplished manually using numerical and graphical techniques instead of a formally developed algorithm. During this period, algorithm development was concentrated on the mass computation techniques. The basic approach to the mass computation algorithm was to compute a mass using the three lowest TM modal frequencies and then add an empirically derived correction term. A full exposition of the development of the mass computation algorithm and its subsequent integration with a formal modal frequency extraction algorithm cannot be treated in this paper; however, this information will be provided in an upcoming final report for the program.

At the current state of algorithm development, it appears that a mass computation algorithm developed for one basic tank shape, size, internal components, and dielectric medium would be scalable to other tank sizes and dielectric media. If the tank shapes and internal components had the same characteristic equation forms as solutions to their maxwell equation set. If the characteristic equations are of different form, another algorithm would have to be developed. This task is not particularly onerous, because testing of a scale model similar to the bench-top testing effort could provide the necessary data. Indeed, experiments using the bench-top data base to evaluate artificial neural network technology as a much faster and potentially more accurate method of developing the required algorithm is very promising.

## CONCLUSIONS

In all feasibility challenges, the RF modal gaging approach was able to easily meet the  $\pm 5$  percent of full-load criteria and come very close to the ultimate  $\pm 1$  percent of full-load accuracy goal. Reduction of the gaging approach to specific hardware should pose no significant problems to currently available technology.